ALS Plant Research at NASA's Kennedy Space Center

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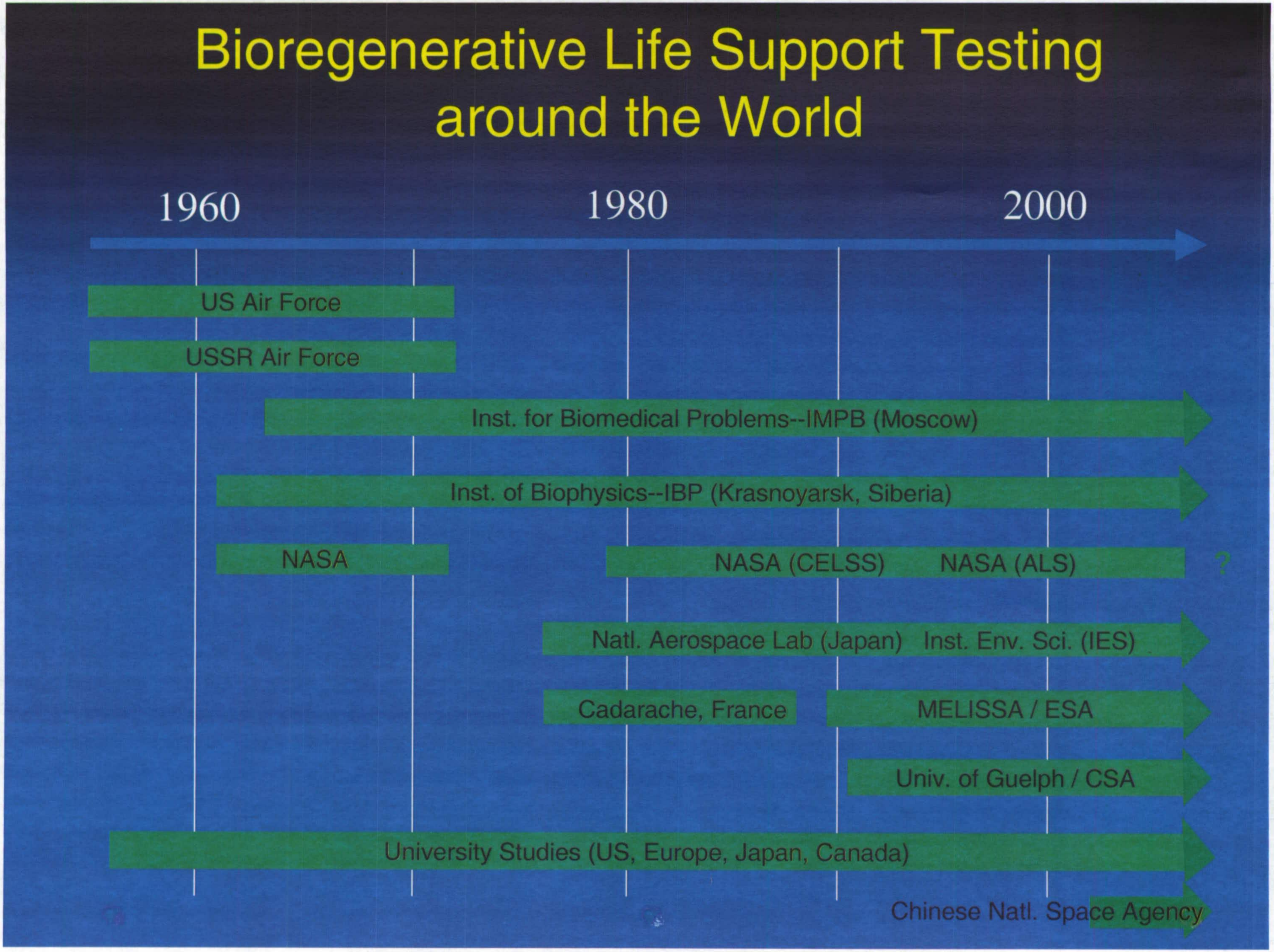
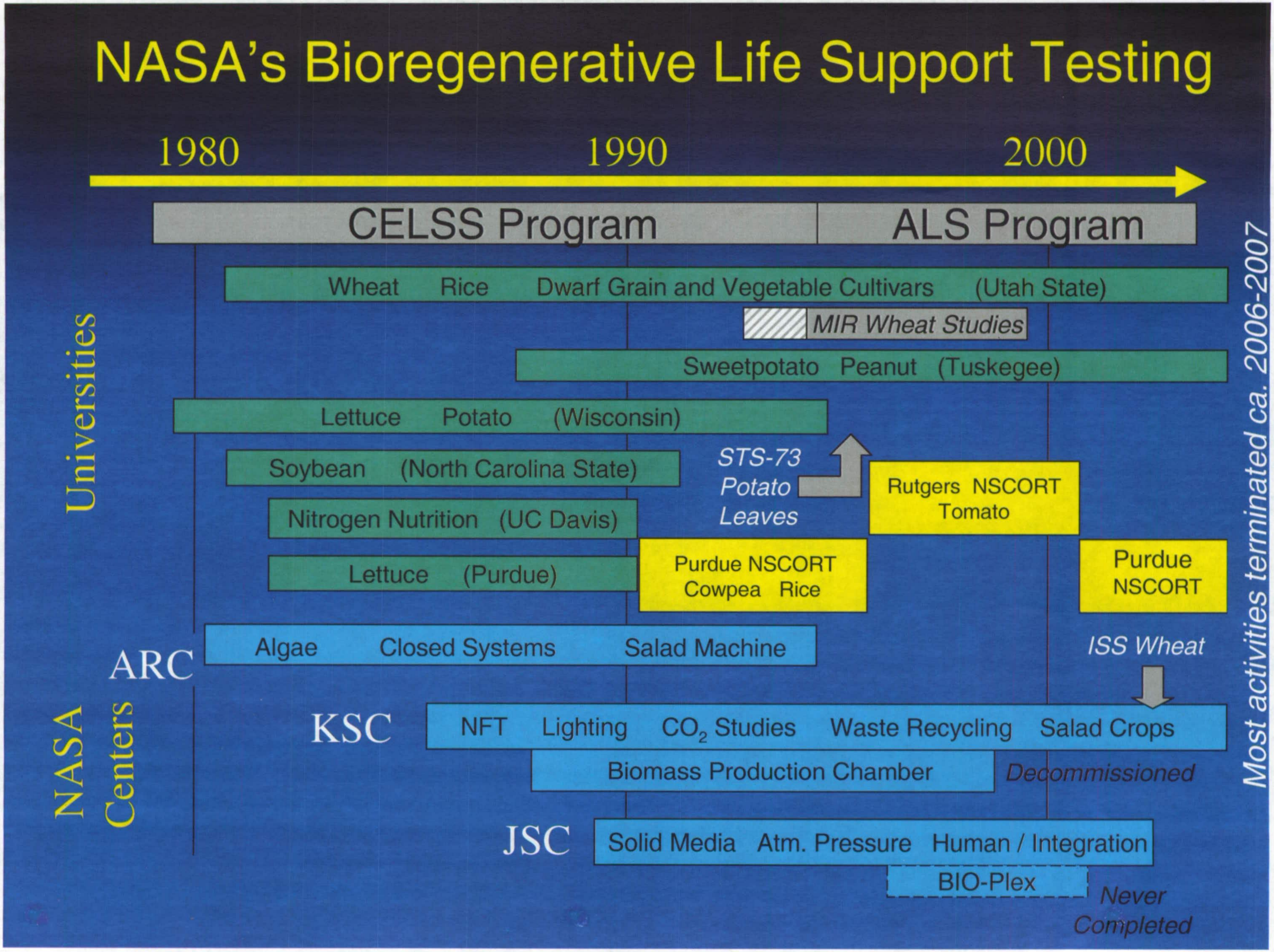
International Symposium on Closed Experimental Systems for Modeling ^{14}C Transfer

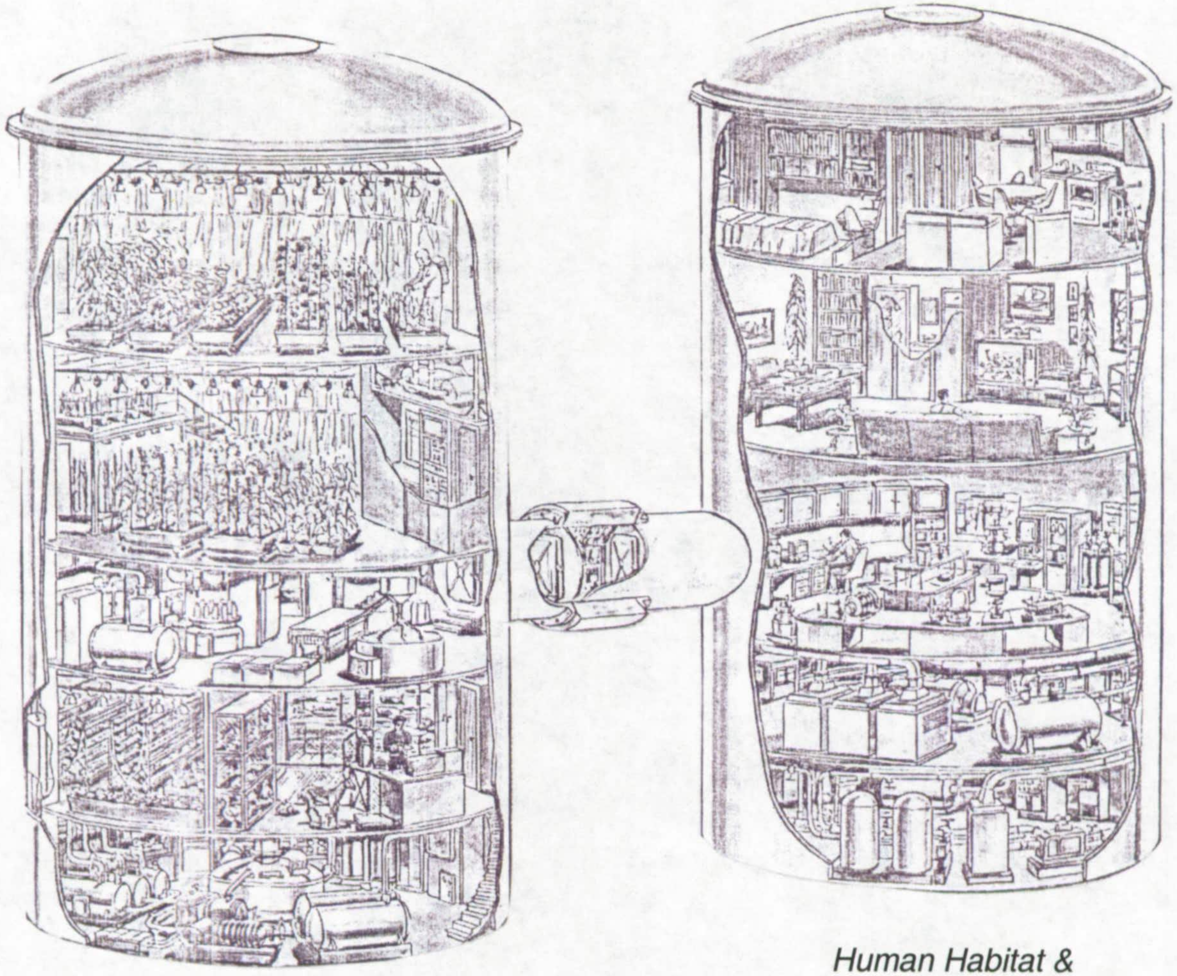
Rokkasho-mura, Aomori, Japan
15 Nov 2007


Bioregenerative Life Support Testing around the World
1960
1980
2000
US Air Force
USSR Air Force
Inst. for Biomedical Problems--IMPB (Moscow)
Inst. of Biophysics--IBP (Krasnoyarsk, Siberia)
NASA
NASA (CELSS)
NASA (ALS)
?
Natl. Aerospace Lab (Japan)
Inst. Env. Sci. (IES)
Cadarache, France
MELISSA / ESA
Univ. of Guelph / CSA
University Studies (US, Europe, Japan, Canada)
Chinese Natl. Space Agency


NASA's Bioregenerative Life Support Testing
1980
1990
2000
CELSS Program
ALS Program
Universities
Wheat Rice Dwarf Grain and Vegetable Cultivars (Utah State)
MIR Wheat Studies
Sweetpotato Peanut (Tuskegee)
Lettuce Potato (Wisconsin)
Soybean (North Carolina State)
STS-73 Potato Leaves
Rutgers NSCORT Tomato
Nitrogen Nutrition (UC Davis)
Lettuce (Purdue)
Purdue NSCORT Cowpea Rice
Purdue NSCORT
NASA Centers
ARC
Algae Closed Systems Salad Machine
ISS Wheat
KSC
NFT Lighting CO2 Studies Waste Recycling Salad Crops
Biomass Production Chamber
Decommissioned
JSC
Solid Media Atm. Pressure Human / Integration
BIO-Plex
Never Completed
Most activities terminated ca. 2006-2007

Proposed CELSS Testbed for Kennedy Space Center, 1978

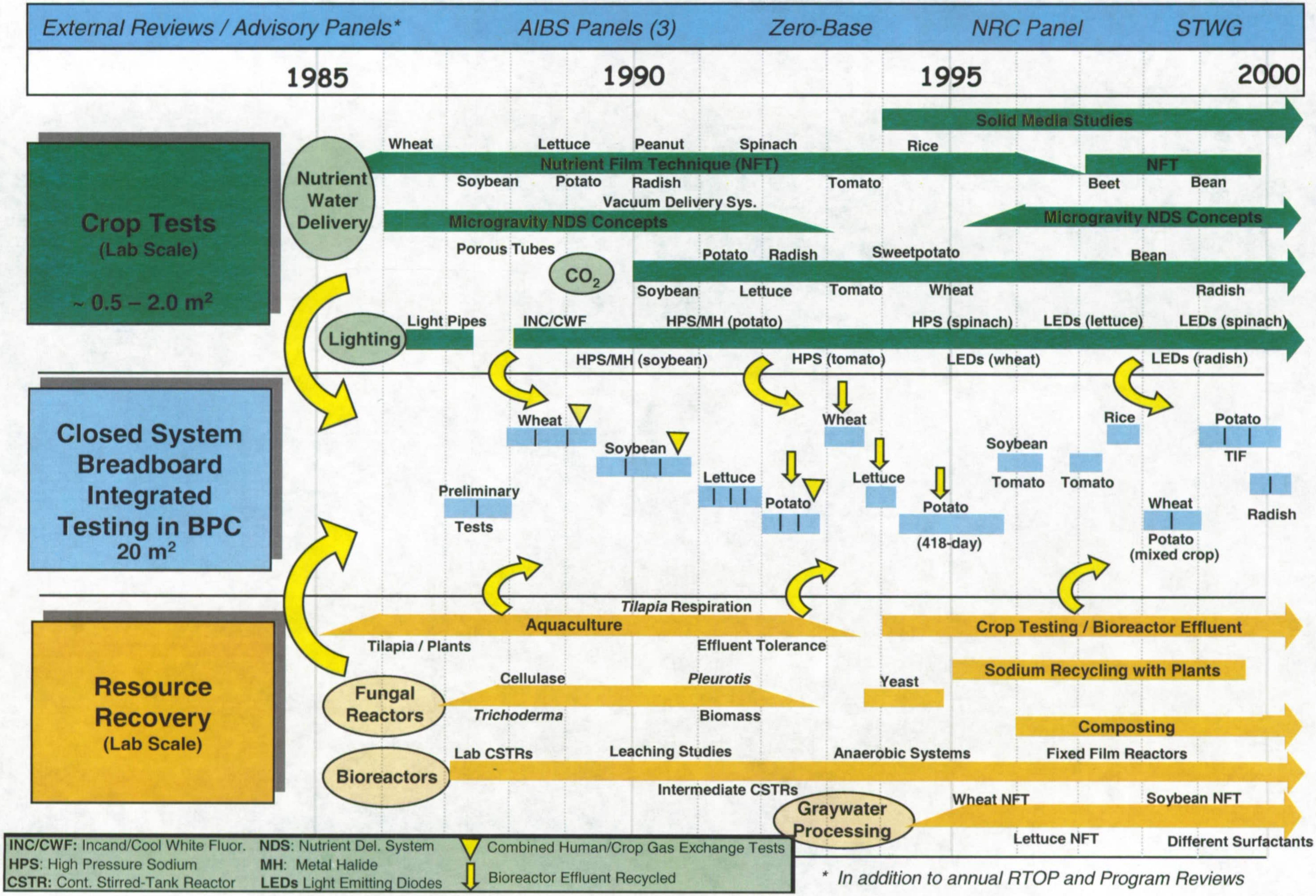
Apollo Hypobaric Chambers O&C Bldg.



Human Habitat & Waste Processing

Crop Production Module

Kennedy Space Center Bioregenerative Life Support Research

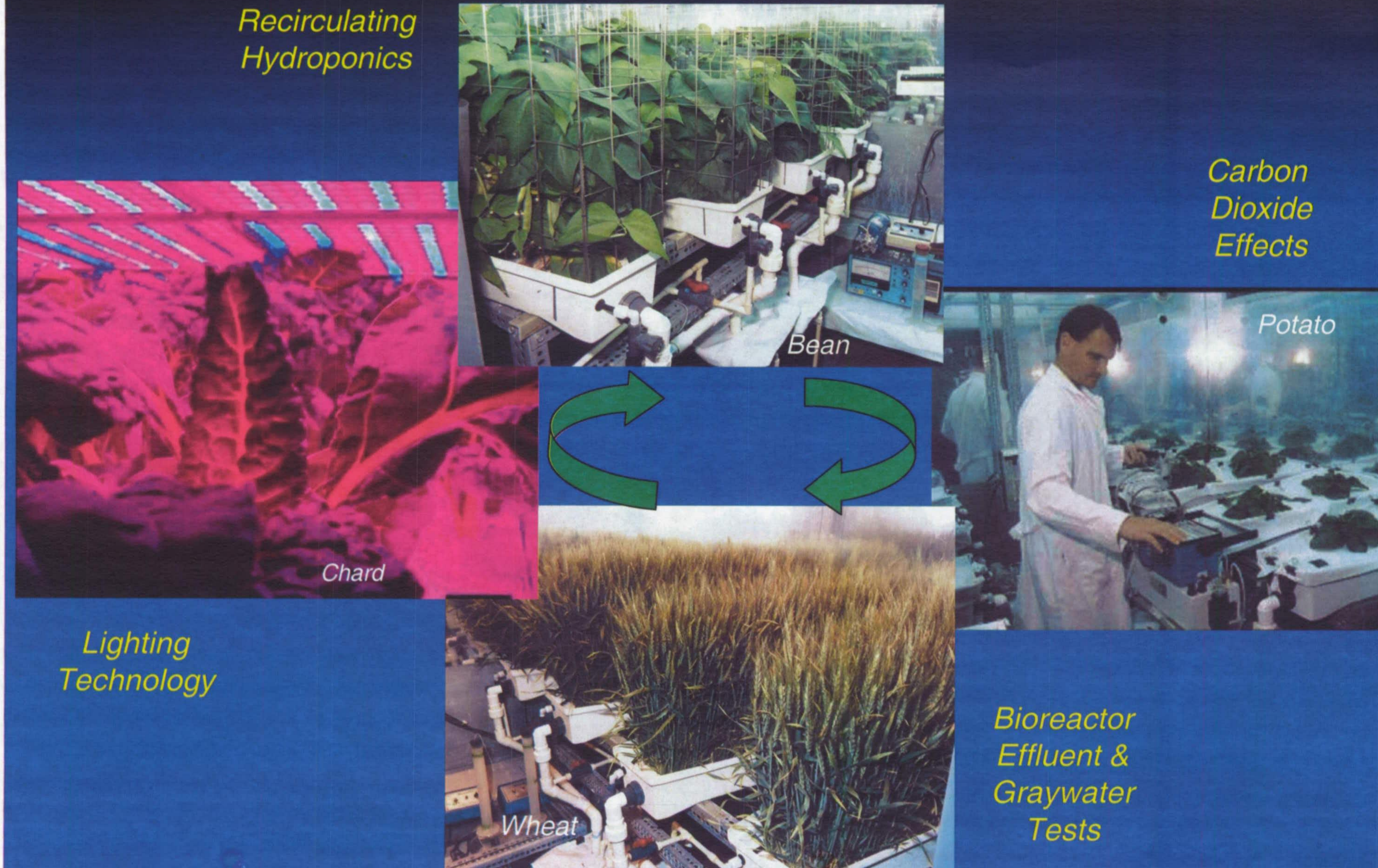


* *In addition to annual RTOP and Program Reviews*

Lab Scale Testing with Plants

Recirculating Hydroponics

Carbon Dioxide Effects



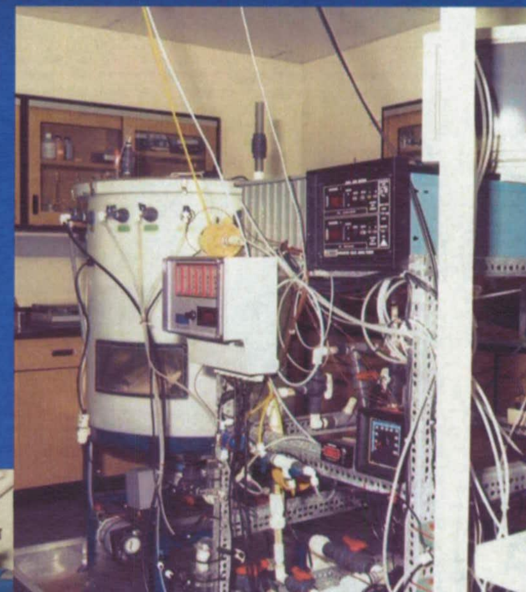
Lighting Technology

Bioreactor Effluent & Graywater Tests

Lab Scale Waste Processing Testing

Large-Scale
Bioreactors (STRs)
for Inedible Biomass

Trichoderma
for Cellulase
Production



Tilipia Fish --
Biomass
Conversion

Intermediate
Scale Reactors
(STRs)

NASA's Biomass Production Chamber

External View - Back

Control Room

Hydroponic System

NASA's Biomass Production Chamber

- Plant growing area--20 m^2
  - 64 hydroponic trays supported on four growing levels
- Atmospheric volume--113 m^3
- Two 30-kW fans for air circulation--400 $m^3\ min^{-1}$
- 96 400-W HPS lamps-- 750 μmol $m^{-2}\ s^{-1}$ PAR
- Two 53-kW chilling units
- Up to 150 kW of heating capability
- Atmospheric leakage rate of ~ 10% vol. day^{-1}

Event Timeline for the KSC Biomass Production Chamber

1985 – 1987
BPC constructed

1987 – 1988 **Early wheat grow-outs as chamber engineering improves: sealed atmosphere and computer control**

1989 – 1992 **Baseline crop studies with wheat, potato, soybean & lettuce**

April 1992 **Separation of upper and lower chambers Added condensate recycling**

May 1992 - June 1992 **Lettuce production on recycled condensate**

June 1992 **- Sept 1993 Testing of biogenic compounds with potato and wheat**

Nov 1993 - Dec 1993 **Lettuce production on recycled minerals**

January 1994 **Breadboard-Scale Aerobic Bioreactor (BSAB) installed for solid waste**

Feb 1994 **- May 1994 Wheat growth on effluent from aerobic bioreactors**

June 1994 **- August 1995 Continuous vs. batch production study of potato on aerobic effluent**

June 1995 **BPC atmosphere connected with BSAB atmosphere**

Oct 1995 - Jan 1996 Baseline crop study with tomato and soybeans

Feb 1996 **- April 1996 Atmospheric study with tomato**

June 1996 **- Dec 1997 Mixed wheat and potato crops in same environment**

June 1997 **Addition of ALSARM robotic manipulator to upper chamber**

Mar 1998 - Oct 2001 Development of monitoring and control software (ALSACT)

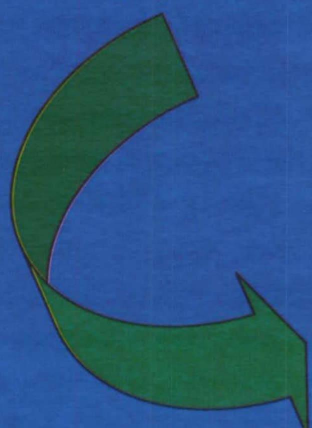
Oct 1999 – Aug 2000 Potato tuber induction factor (TIF) studies phase I

Jan 2001 **– Oct 2001 Potato Tuber Induction Factor (TIF) Studies Phase II**

Nov. 2001
BPC Decommissioned

BPC Crop Tests (Wheat)

planting

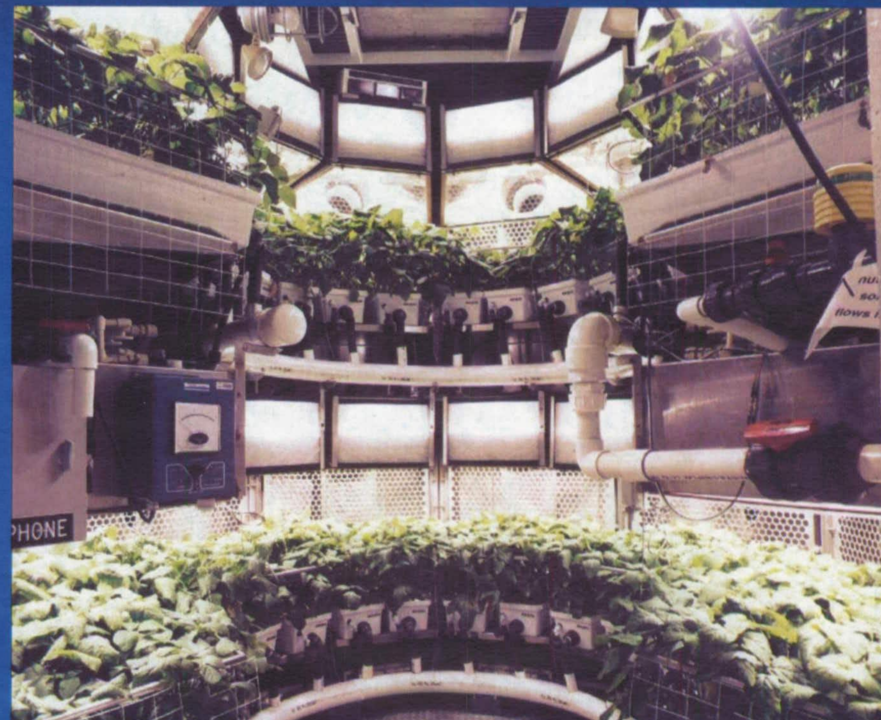


harvest

Lettuce

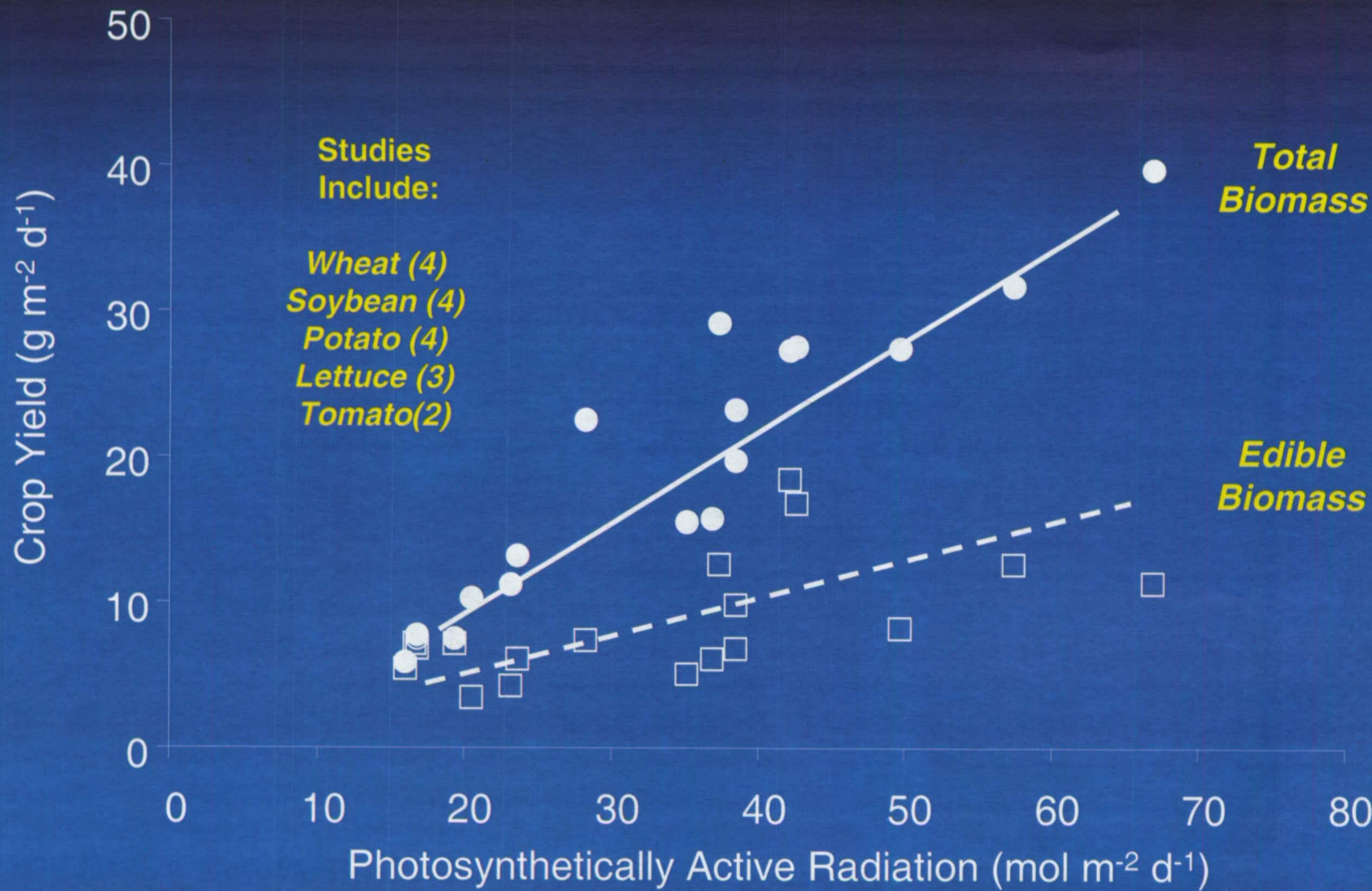
Potato

Soybean



Effect of Light (PAR) on Crop Yield

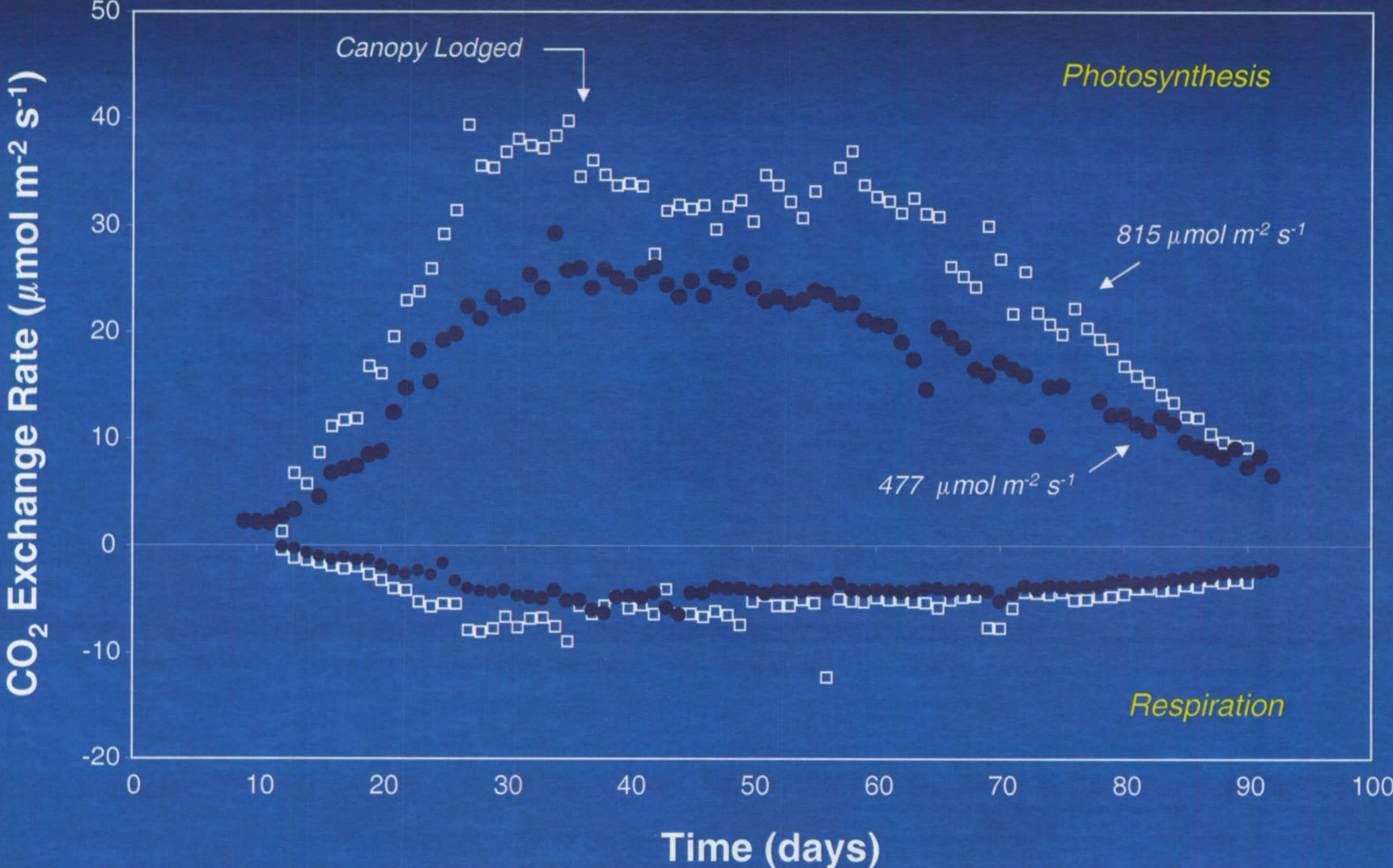
(from NASA Biomass Production Chamber)



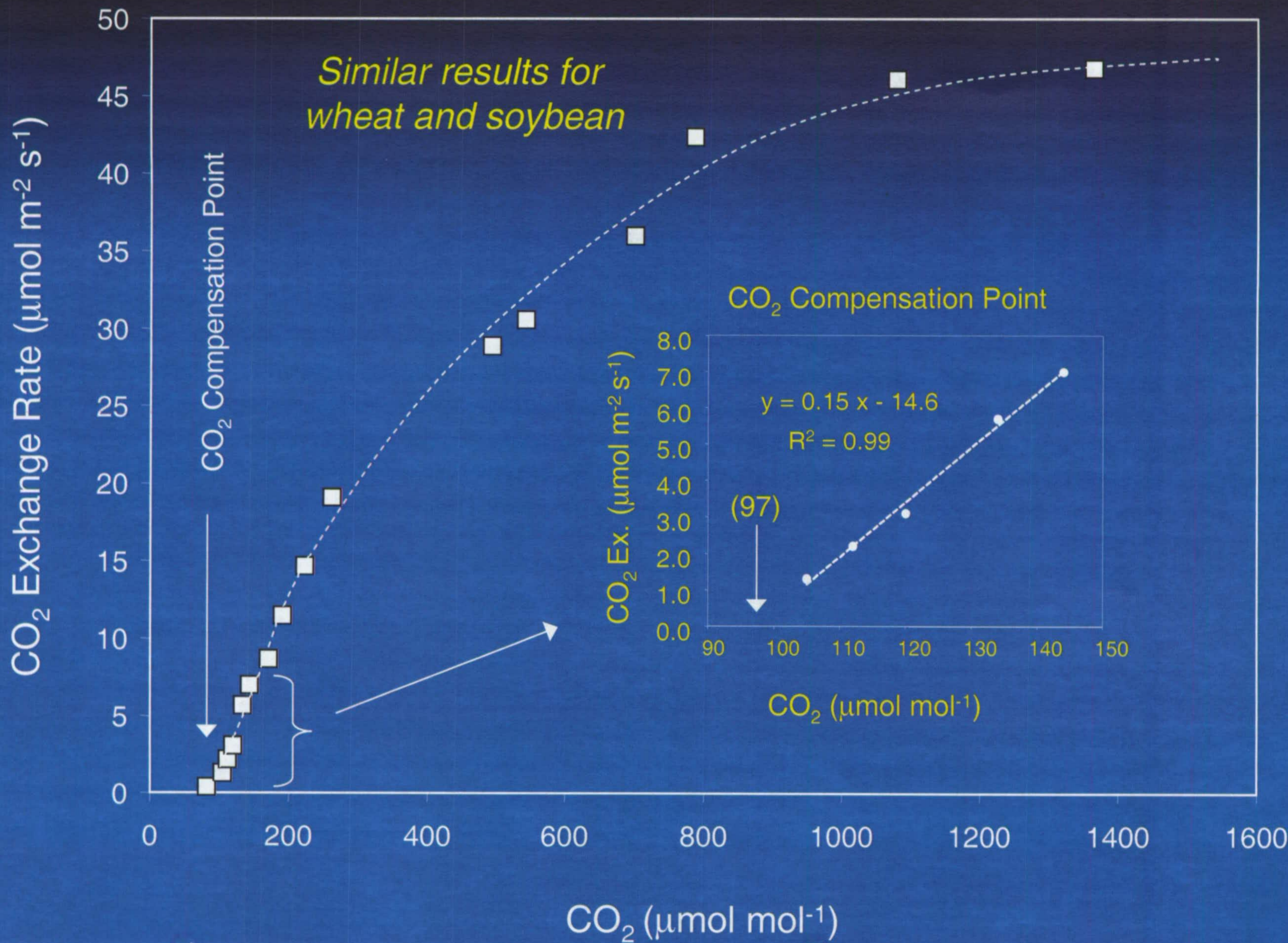
Closed System Studies from BPC Studies

- CO_2 Exchange Rates
  - photosynthesis and respiration
  - influence of environmental factors
- Volatile Organic Compounds--VOCs
  - ethylene
- Effects of Super-Elevated CO_2
- Water Use Rates
- Nutrient Uptake and Movement

Photosynthesis and Respiration of Soybean Stands



Effect of CO_2 Concentration on Photosynthesis (potato)

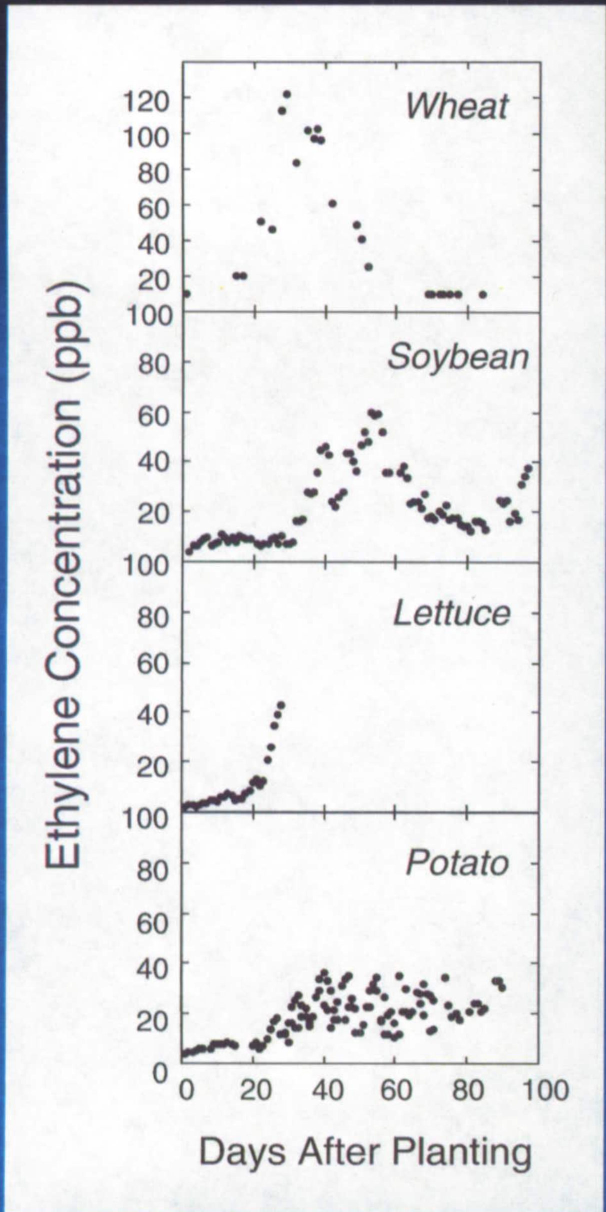


Some Biogenic Volatiles in Closed Systems

Humans [1]	Plants [2]
acetaldehyde	benzaldehyde
acetone	2-butanone
ammonia	carbon disulfide
n-butyl alcohol	ethylene
carbon monoxide	2-ethyl-1-hexanol
caprylic acid	heptanal
ethanol	hexanal
ethyl mercaptan	2-hexen-1-ol acetate
hydrogen	isoprene
hydrogen sulfide	limonene
indole	2-methylfuran
methanol	nonanal
methane	ocimene
methyl mercaptan	α-pinene
propyl mercaptan	β-pinene
pyruvic acid	α-terpinene
skatole	tetrahydrofuran
valeraldehyde	tetramethylurea
valeric acid	thiobismethane

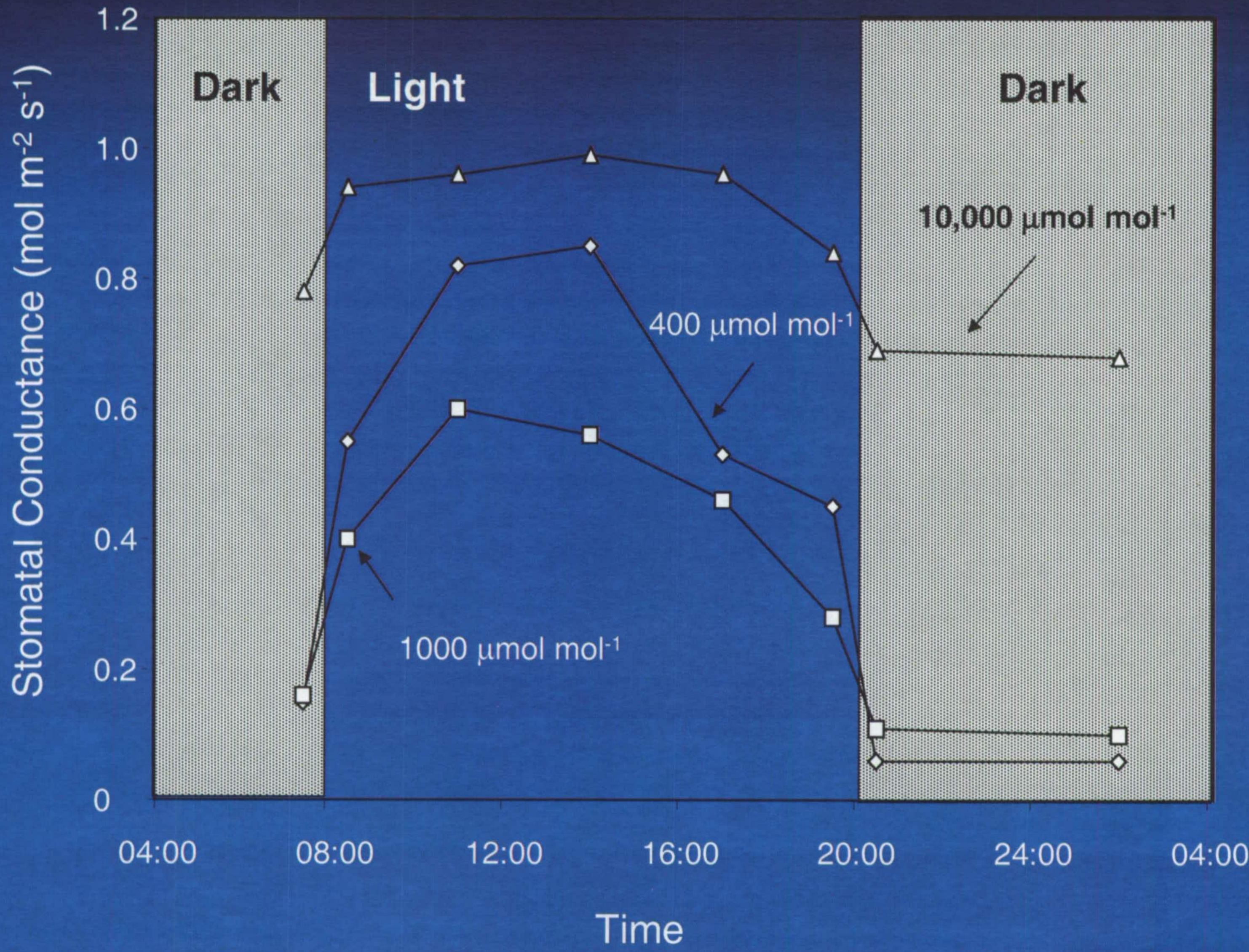
1 Reed and Coulter (1999).
2 From NASA BPC Studies (Batten et al.,1996; Stutte and Wheeler,1997).

Ethylene Accumulation

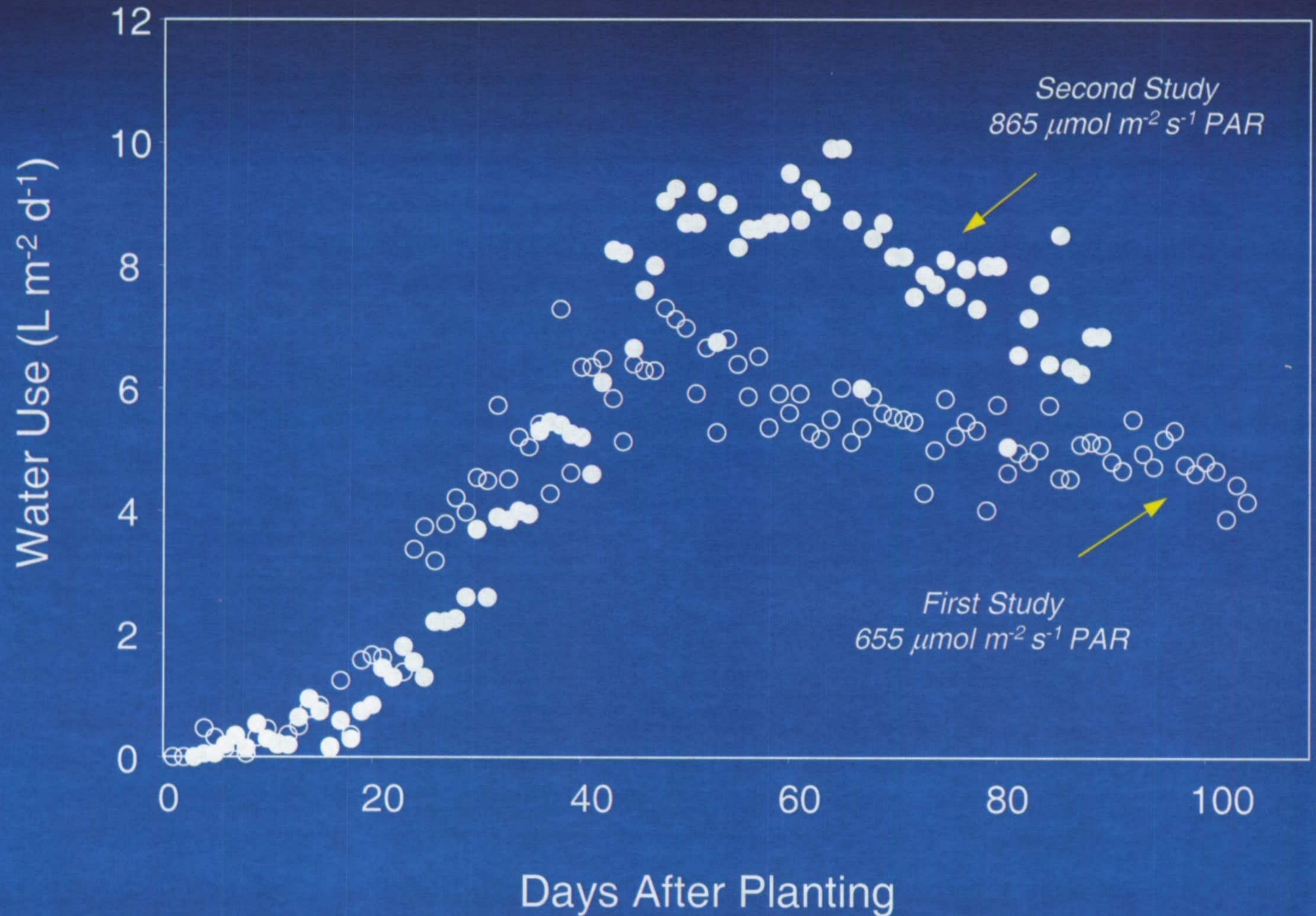


Epinastic
Potato Leaves
at ~40 ppb

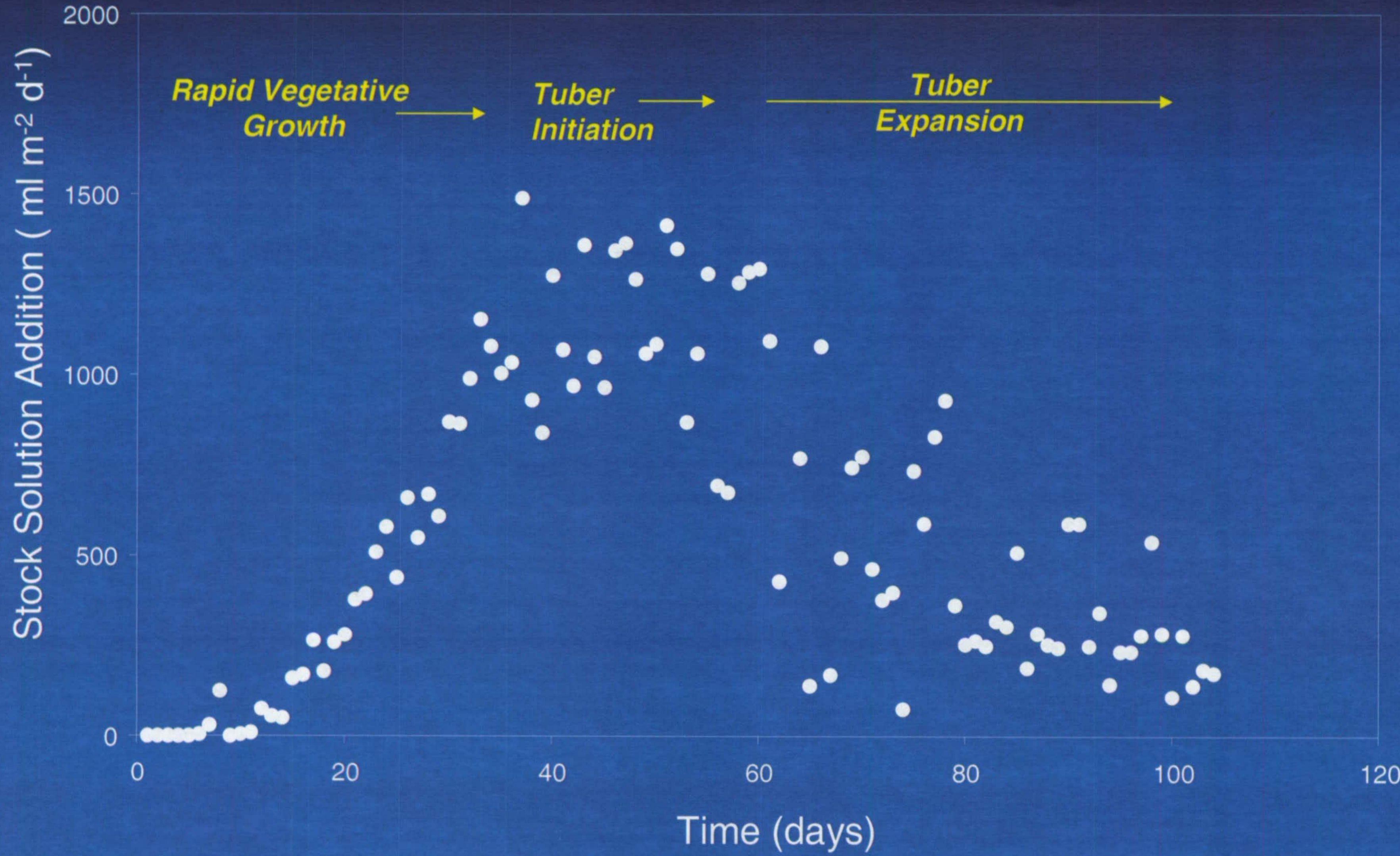
Super-Elevated CO_2 Effects on Stomata



Evapotranspiration from Plant Stand (potato)



Nutrient Uptake by Plants (potato)



Crop / Date	Photoper. [2] / PPF	Daily PAR	Total Biomass			Edible Biomass		
	(h) /(μmol m^{-2} s^{-1})	(mol m^{-2} d^{-1})	(kg m^{-2})	(g m^{-2} d^{-1})	(g mol^{-1} PAR)	(kg m^{-2})	(g m^{-2} d^{-1})	(g mol^{-1}PAR)
Wheat 881	24 / 666	57.5	2.31	31.6	0.55	0.92	12.6	0.22
Wheat 891	20 / 535	38.5	1.89	23.1	0.60	0.55	6.7	0.17
Wheat 892	20 / 691	49.7	2.21	27.3	0.55	0.66	8.1	0.16
Wheat 931	20 / 930	67.0	3.21	39.6	0.59	0.91	11.3	0.17
Wheat 941	20/1177	84.7	3.33	39.7	0.47	0.95	11.4	0.13
Soybean 891	12 / 815	35.2	1.33	15.5	0.44	0.43	5.0	0.14
Soybean 901	12 / 477	20.6	0.95	10.2	0.50	0.32	3.4	0.17
Soybean 902	10 / 644	23.2	1.04	11.2	0.48	0.39	4.2	0.18
Soybean 951	12 / 845	36.5	1.35	15.7	0.43	0.52	6.0	0.16
Lettuce 902	16 / 280	16.1	0.14	5.8	0.36	0.13	5.4	0.34
Lettuce 911	16 / 293	16.9	0.18	7.5	0.44	0.16	6.7	0.40
Lettuce 921	16 / 336	19.4	0.18	7.5	0.39	0.17	7.1	0.37
Lettuce 931	16 / 291	16.8	0.20	7.7	0.46	0.19	7.1	0.42
Potato 911	12 / 655	28.3	2.28	22.4	0.79	0.74	7.3	0.26
Potato 912	12 / 866	37.4	2.53	29.1	0.78	1.10	12.6	0.34
Potato 921[3]	12 / 917	42.2	2.77	27.2	0.64	1.88	18.4	0.44
Potato 931[3]	12-16 / 849	42.7	2.74	27.4	0.64	1.71	16.7	0.40
Potato 941[4]	12 / 791	34.2	13.62	32.6	0.95	8.35	20.0	0.58
Tomato 951	12 / 549	23.7	1.10	13.1	0.55	0.51	6.1	0.26
Tomato 961	12 / 894	38.6	1.69	19.6	0.51	0.85	9.8	0.25

Crop / Date	Days of Operation	Total Biomass	Edible Biomass	CO_2[1] Fixed	O_2[1] Produced	Water Collected
	(d)	(kg)	(kg)	(kg)	(kg)	(kg)
Wheat 881	77	23.06	9.24	35.5	25.8	3615
Wheat 891	86	37.76	11.01	58.2	42.3	6903
Wheat 892	85	44.24	13.12	68.1	50.7	7809
Wheat 931	85	64.11	18.25	98.7	71.8	7500
Wheat 941	84	66.68	19.07	102.7	74.7	7600
Soybean 891	90	26.62	8.58	45.0	32.7	7758
Soybean 901	97	18.94	6.34	32.0	23.3	8211
Soybean 902	97	20.80	7.79	32.5	25.6	8450
Soybean 951	90	13.51	5.18	22.8	16.6	2594
Lettuce 902	28	2.84	2.60	4.2	3.1	976
Lettuce 911	28	3.54	3.24	5.2	3.8	998
Lettuce 921	28	3.57	3.36	5.2	3.8	1000
Lettuce 931	30	3.99	3.71	5.9	4.3	1074
Potato 911	105	45.58	14.89	68.4	49.7	8778
Potato 912	90	50.67	22.03	76.2	55.4	9361
Potato 921	105	55.42	37.64	83.1	60.5	7954
Potato 931	105	55.88	34.12	83.8	61.0	8546
Potato 941	418	272	167	409	296	28446
Tomato 951	(84)	11.03	5.15	16.6	12.1	3426
Tomato 961	87[8]	33.87	17.06	50.9	37.0	12,700
Total	2243	880	409	1344	980	149390

Some Conclusions

- The Biomass (Plant) Production Chamber at Kennedy Space Center was operated as a closed testbed for 10 years (1988-1998).
- Results showed a close match between CO_2 flux and biomass production data.
- Manipulations of light, CO_2, and temperature showed expected responses in photosynthesis and respiration.
- A range of crop species (seed, vegetative, tuberous, and fruit) were grown successfully in recirculation hydroponics.
- Volatile organic compounds could be tracked throughout growth and development.
- No major equipment failures occurred, but some sensors, lamps, and pumps had to be replaced during the 10 years.

Some Conclusions

- The best gas exchange rates suggest that 20-25 m^2 of crops grown at ~750 $\mu mol\ m^{-2}\ s^{-1}$ PAR would provide the O_2 and CO_2 removal for one human.
- The best yields suggest that about 50 m^2 of crops grown at ~750 $\mu mol\ m^{-2}\ s^{-1}$ would provide the food (calories) for one human.

Some Conclusions

- After 10 years of near-continuous operation of the Biomass Production Chamber, system failures typically involved the support hardware, electrical power, and software.
- The plants proved to be very reliable and resilient as life support machines.

The End of the Biomass Production Chamber